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DEVELOPMENT AND RESULTS OF A FIRST GENERATION LEAST EXPENSIVE APPROACH TO FISSION: MODULE TESTS AND RESULTS

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ABSTRACT

The use of resistance heaters to simulate heat from fission allows extensive development of fission systems to be performed in non-nuclear test facilities, saving time and money. Resistance heated tests on the Module Unfueled Thermal-hydraulic Test (MUTT) article has been performed at the Marshall Space Flight Center. This paper discusses the results of these experiments and identifies future tests to be performed.

INTRODUCTION

Successful development of space fission systems will require an extensive program of affordable and realistic testing. In addition to tests related to design/development of the fission system, realistic testing of the actual flight unit must also be performed. Testing can be divided into two categories, non-nuclear tests and nuclear tests.

Full power nuclear tests of space fission systems are expensive, time consuming, and of limited use, even in the best of programmatic environments. Factors to consider when performing nuclear tests include the following:

1. Time and cost associated with fabricating and handling the test article;
2. Non-flight-prototypic modifications to the test article required to enable ground testing;
3. Required modifications to existing nuclear facilities to enable testing;
4. Time and cost associated with testing the article at a nuclear facility;
5. Time and cost associated with radiological cool down and transfer/shipping to a hot cell;
6. Expense and slow pace of assessing failures in a hot cell environment; and
7. Limited ability to correctly identify failure mechanisms in a hot cell environment.

History provides examples related to the seven concerns listed above. During the highly successful Rover Nuclear Rocket Development Program, it still took nearly four years to move from the Pewee ground nuclear test (1968) to the follow-on nuclear test, the Nuclear Furnace 1 test in 1972 (Koenig, 1986). The first five full ground nuclear power tests of the program (Kiwi A, Kiwi A', Kiwi A3, Kiwi B1A, Kiwi B1B, total cost >\$1B FY00 equivalent) all resulted in massive fuel damage due to thermal hydraulic problems and flow-induced vibrations. These problems were not resolved until non-nuclear cold-flow tests were performed. During the SP-100 program, tens of millions of dollars were spent attempting to modify the Hanford Site 309 Building to allow a full ground nuclear test of an SP-100 system (Carlson, 1993). In addition, the system to be tested (SP-100 Ground Engineering System) was significantly different from the SP-100 Generic Flight System (Fallas, 1991). The Hanford Site 309 Building was selected in 1985 to be the site of the Ground Engineering System test (Baxter, 1991). At the end of the SP-100 program (nearly 10 years later)

significant modifications still remained before nuclear tests could be performed in the building. During the Thermionic Fuel Element Verification Program it frequently took more than a year for thermionic fuel elements (TFEs) and TFE components to be removed from the test reactor, shipped, and readied for post-irradiation examination (PIE). When PIE was performed, limited data was obtained due to the expense, time, and limited equipment availability associated with working in a hot cell (Ranken, 1994). Neither the Rover program, nor the SP-100 program, nor the TFEVP led to the flight of a space fission system.

Non-nuclear tests are affordable and timely, and the cause of component and system failures can be quickly and accurately identified. The primary concern with non-nuclear tests is that nuclear effects are obviously not taken into account. To be most relevant, the system undergoing non-nuclear tests must thus be designed to operate well within established radiation damage and fuel burn up limits. In addition, the system must be designed such that minimal assembly is required to move from non-nuclear testing mode to a fueled system operating on heat from fission. If the system is designed to operate within established radiation damage and fuel burn up limits while simultaneously being designed to allow close simulation of heat from fission using resistance heaters, high confidence in fission system performance and lifetime can be attained through a series of non-nuclear tests. Any subsequent operation of the system using heat from fission instead of resistance heaters would then be viewed much more as a demonstration than a test - i.e. the probability of system failure would be very low.

All future space fission system development programs could benefit from optimizing the use of realistic non-nuclear tests. First-generation systems will benefit the most, as they are most likely to operate within established radiation damage and fuel burn up limits. Although advanced fission systems will require extensive nuclear testing, experience and support gained from the in-space utilization of earlier systems should facilitate their development. Testing of the MUTT at the Marshall Space Flight Center is a first step towards the testing of nuclear systems in a non-nuclear test facility. The MUTT is the first test in a series of tests for the First Generation Least Expensive Approach to Fission (FiGLEAF) program proposed by the Propulsion Research Center (PRC) at NASA/MSFC.

The MUTT test series has five top-level goals:

1. Demonstrate that realistic non-nuclear testing can be used to resolve thermal hydraulic and other issues associated with space fission system development.
2. Demonstrate that the eventual user of space fission systems (in this case NASA) can be heavily involved in all aspects of space fission system development.
3. Demonstrate the desirability of a modular core design that allows issues to be resolved on a module level prior to fabrication and test of a full core.
4. Demonstrate the superiority of hardware-based technology assessment over the never-ending cycle of paper studies often associated with advanced system development.

5. Experience gained from the MUTT test series will be directly applicable to full-core tests slated to begin later in FY00.

Specific technical goals of MUTT test series include the following:

1. Gain experience using resistance heaters to realistically simulate heat from fission. Test module to thermal design limits by demonstrating capability of module to operate at 1477°C. (1750 K).
2. Demonstrate energy transfer capability of the heat pipe (greater than 1 kW) Test heat pipe to thermal design limits by demonstrating a heat pipe operating temperature of 1027°C (1300 K).
3. Demonstrate heat pipe operation at extreme transients (fast start followed by instantaneous shutdown).
4. Demonstrate direct thermal propulsion by introduction of cold gas (ambient conditions) and extraction of hot gas (900°C) from the chamber.

Development of instrumentation techniques for flow, temperature, and other measurements in a simulated fission system.

NOMENCLATURE

TFE	Thermionic Fuel Element
TFEVP	Thermionic Fuel Element Verification Program
PIE	post-irradiation examination
FiGLEAF	First Generation Least Expensive Approach to Fission
PRC	Propulsion and Research Center
NASA	National Aeronautics Space Administration
MSFC	Marshall Space Flight Center

EXPERIMENTAL APPARATUS

This MUTT is a 5.08-cm diameter, 45-cm long pure tungsten "block", which represents a module with 6 "fuel" pins surrounding a central molybdenum-lithium heat pipe. It is supported at each end by stainless steel end caps that are insulated with a molybdenum foil to prevent reaction with the block, see Figure 1. A support member, mounted to an extension elbow, holds the two end caps. Fingers from the elbow capture the internal diameter of two opposing viewports to hold the MUTT in place. The block is insulated with graphfoil insulation (not shown).

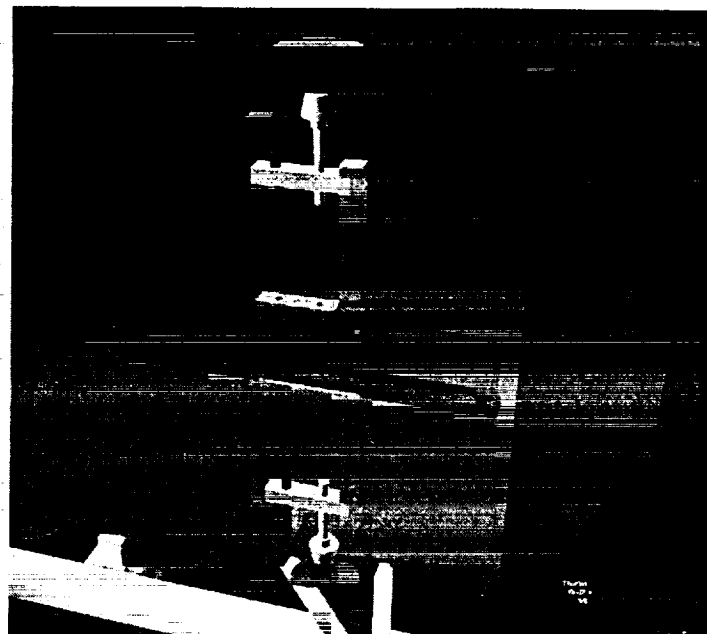


FIGURE 1. Module Unfueled Thermal-hydraulic Test Article in PEST.

The tungsten block is heated with 6 resistance heaters (simulating "fuel" pins) 50 to 53 cm long and 1.17-cm diameter to simulate the heat produced by nuclear fuel elements. The high-temperature boron nitride heaters, capable of reaching over 2000 K, were designed and produced by Advanced Ceramics Inc, of Lakewood, OH. They are connected in two heater pairs, which are connected in parallel to an electrical feed through in the chamber. Fourteen gauge copper is connected the heaters to the feed through. This provides MUTT with a maximum available power of 3 kW to each heater (operating temperature limit, not power available limitation). Digital output multimeters deliver total heater current and voltage information to the data acquisition system. Temperature readings are obtained with an optical pyrometer and thermocouples. Representative interstitial holes run parallel to the "fuel pins" for direct thermal heating of gases. Gaseous helium passing through module simulates direct heating.

A molybdenum-lithium heat pipe, developed at Los Alamos National Laboratory (Reid, 1999), is inserted in the center hole of the tungsten block and supported at the far end by a stainless steel support bar. The heat pipe is 145-cm long, 1.27-cm outer diameter, and has a crescent-annular wick structure consisting of 7 layers of 400 mesh sintered molybdenum screen. Before delivery to MSFC, the heat pipe was tested at Los Alamos where it demonstrated radiation coupled operation to the environment of 1 kW at 1450 K. The heat pipe is instrumented with 9 type C thermocouples tack welded to the heat pipe on a nickel foil interlayer. The distance between the first 8 thermocouples is approximately 10 cm and beginning 10 cm from the end of the block. The distance between the last two thermocouples is about 20 cm. One thermocouple was attached

to the tungsten block between the block and one thermocouple was attached to the chamber wall of PEST. An optical pyrometer is used to verify the accuracy of the thermocouple data. The thermocouple temperature data was directed to the data acquisition system. Figure 2 shows the position of the heat pipe, the resistance heaters, and the gas entrance.

RESULTS OF EXPERIMENT

The first series of tests verified the test set-up and verified the ability of the heaters to heat the module (neither gas flow or heat pipe were included in these tests). The heaters were set at a constant power level and the uninsulated module temperature was monitored. The power level was kept at 7.2 kW. It appeared that module temperature reached steady state. This occurred at a terminal voltage across each heater of approximately 11 V and kept at the constant level until the module reached steady state. This procedure continued until the maximum available current that could be delivered by the power supply was reached. This corresponded to a power level of approximately 7 kW delivered to the module. The maximum temperature of the module was approximately 663 K. Figure 2 shows the temperature profile for this test. Although the temperature profile was similar for each power level, at 7.2 kW the module temperature had reached steady state fairly quickly. Figure 3

"fuel pins" (heaters) _____
heat pipe _____
gas _____

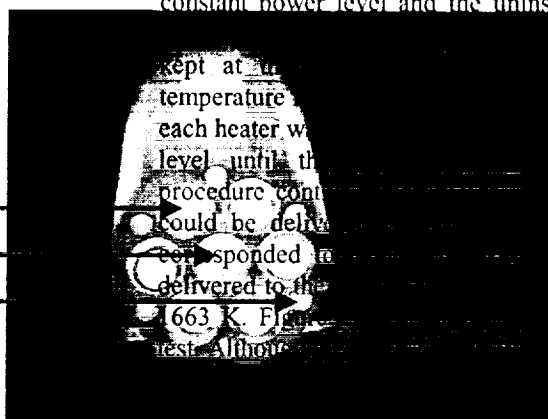


FIGURE 2. Position of heatpipe, heaters, and gas entrance on MTT

Helium is injected through a gas feed through to a manifold that distributes the gas into six feeds that connect to the inlet side end cap of the tungsten block. The gas is then heated by the block and vented into the chamber where it is pumped out. The exhaust end cap is outfitted with thermocouples positioned over the gas exhaust holes to record change in temperature. Inlet temperature of the gas is measured prior to injection into the chamber. Gas flow rate is monitored and controlled by an MKS flow control unit.

Pressure in the chamber was monitored using multiple vacuum thermocouple gauges for pressures above 10^{-3} Torr. For pressures below the capability of the thermocouple gauge, a cold cathode and Baypert-Albert ion gauge were used. Real-time pressure data was gathered both by a stand-alone Varian vacuum multi-gauge controller and LabView.

LabView software and corresponding National Instruments hardware was selected as the data acquisition and control (DAC) software due to its high level of industry implementation and versatility. LabView is highly modular and has been customized to perform most all the routine operations standard to PEST. The data acquisition and control hardware consisted of a SCXI chassis outfitted with cards specific to MTT needs. The chassis contained a thermocouple card, a control card for operation of valves and switches, and card to handle the pressure information. Interface with the SCXI chassis was by computer running LabView software. LabView collected and assembled the data as well as monitored most aspects of the experiment. All electronic controls and data acquisition devices were located on a rack next to the chamber.

shows the module at approximately 7.2 kW at 4000 s.

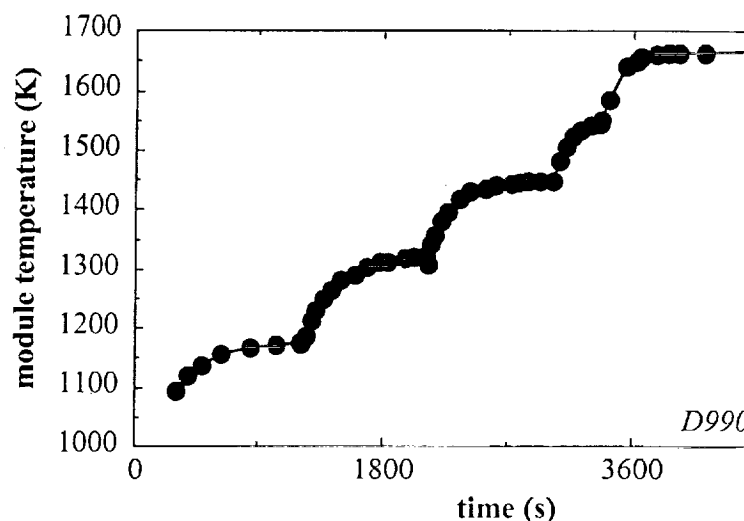


FIGURE 3. Time versus temperature profile for first test of the uninsulated module.

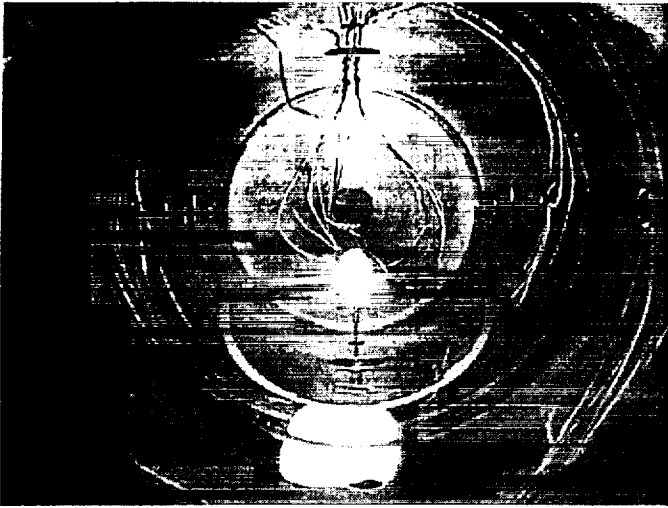


FIGURE 4. The uninsulated module at 7.2 kW and 4000 s.

Radiation calculations verified that the heat rejected from the module was approximately equal to that delivered to the module from the heaters. A second test, carried out with the identical settings and procedures as the first test, yielded the same results as the first test. These two tests verified that the heaters could be used to realistically simulate heat from fission. In an effort to increase the power available to the heaters, the power supply was rewired so an increase in current, resulting in an increase in available power, could be delivered to the heaters. The third test showed that at the same power levels, the time-temperature profiles were identical to the first two tests. The maximum power delivered by the heaters for the third test was approximately 9.2 kW corresponding to a maximum module temperature of 1754 K. These tests provided time temperature profile, which serves as a baseline for determining performance capability of the heat pipe, and demonstrated high temperature test capability.

The next series of tests were to verify the operation of the heat pipe under various operating conditions. Type C thermocouples were installed on both the heat pipe and on the module to record temperatures. The thermocouple on the module served both to verify the optical pyrometer readings from earlier tests and to serve as a frame of reference for the heat pipe thermocouples.

The first heat pipe test was to verify heat-pipe operation, instrumentation hook-up, and test procedure. The first test ran for a total of 115 min and showed successful operation of the heat pipe. Since a slow start-up of the pipe was desired, the power supply was initially set to deliver 60 V (0.12 W), and increased at approximately 10 V increments every 10 min. This brought the heat pipe to a maximum operating temperature of 1220 K after 115 min. Figure 4 shows the thermocouples instrumented heat pipe. Figure 5 shows the thermocouple data over the period of the test.



FIGURE 5 Instrumented molybdenum-lithium heat pipe.

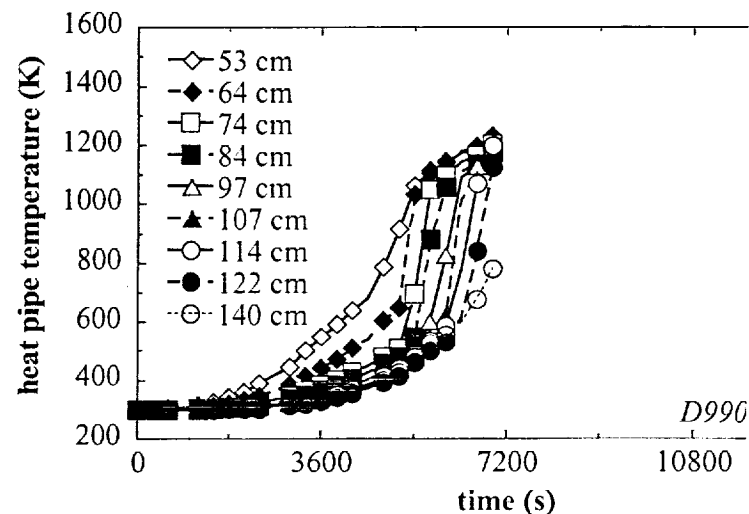


FIGURE 6. Start-up time versus temperature profile for the first heat pipe test.

At the end of the first test, air leaked into the chamber through a defective sight glass. The chamber was flooded with gaseous helium and kept at 1 Torr as the module and heat pipe cooled to ambient conditions. The module was hydrogen cleaned and a second heat pipe test was conducted again to determine the operational capability of the heat pipe and to verify that no damage had occurred. Since a slow start-up of the heat pipe was desired, the power supply was set to deliver 60 V (0.15 W), increasing approximately 15 V every 10 min. This brought the heat pipe to a maximum operating temperature of 1395 K, corresponding to a heat transfer rate of at least 1.8 kW after 245

min. Figure 6 shows the thermocouple data over the period of the test. The data showed successful heat pipe operation with the entire heat pipe at an operating temperature greater than that of the first test (>1220 K). At the end of the 245 min, the heat pipe was isothermal and the test terminated. This demonstrated that the heat pipe was able to operate successfully, even when exposed to worst-case conditions. Both an optical pyrometer and a thermocouple were used for measuring the temperature of the thermocouple on the heat pipe that was closest to the module (TC1). The difference between both methods varied by only a maximum of 1.5 %, verifying the "goodness" of the data from the first three tests which used only the optical pyrometer. A third test was carried out in which the heat pipe was brought to isothermal (1448 K corresponding to a heat transfer rate of at least 3 kW) in 55 minutes. These series of tests showed the operability of a heat pipe under various start-up transients (fast and slow), even when exposed to extreme conditions. This test series also verified the restart capability of the heat pipe.

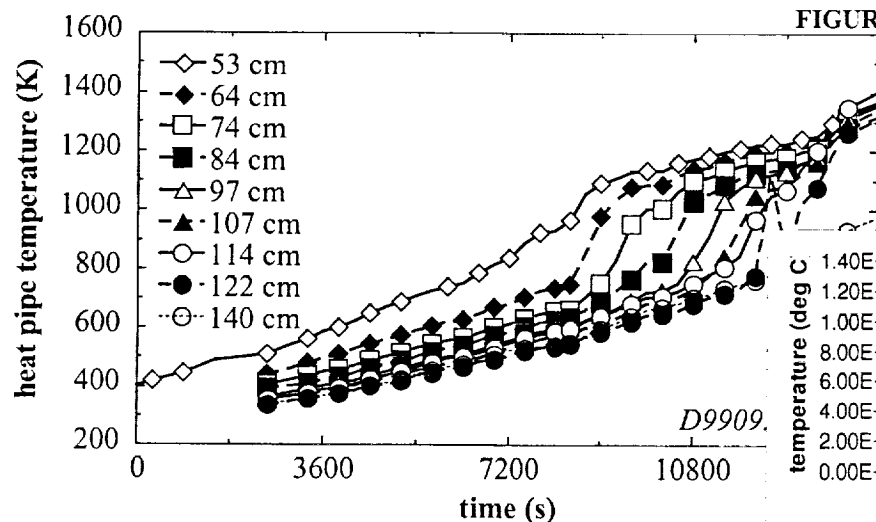


FIGURE 7. Start-up time versus temperature profile for the second heat pipe test.

The final series of tests was to demonstrate the ability of gas to transfer heat from the module. To avoid corona effects (due to the gas used and the voltage of the heaters), the module was raised to an operating temperature of 1200 C. Figure 7. shows the gas system around the tungsten module. At this temperature, the power was turned off and gas was flowed through the system. Although the gas did not reach the desired 900 C, the gas and module temperatures were the same during gas flow indicating that the gas did extract heat from the module tracking the module temperature exactly. Figure 8 shows the temperature at the end of one of the gas holes and the temperature of the tungsten module as a function of time. These tests showed that gas could extract heat from the module (direct

thermal thrust), and that the tungsten block can withstand the thermal stresses.

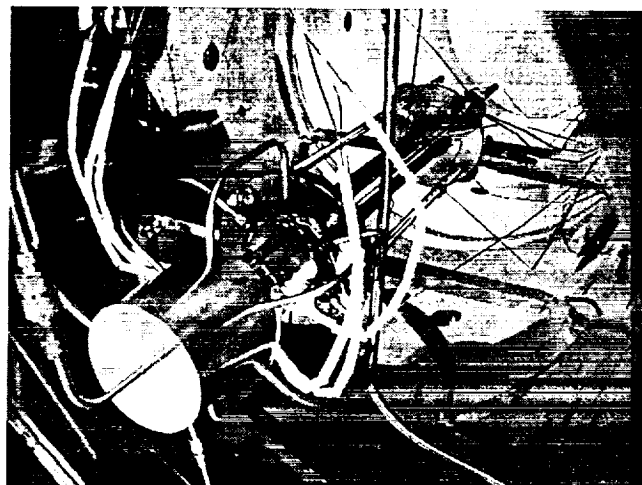


FIGURE 8. Gas System. Introduction of ambient gas into module and exit into chamber.

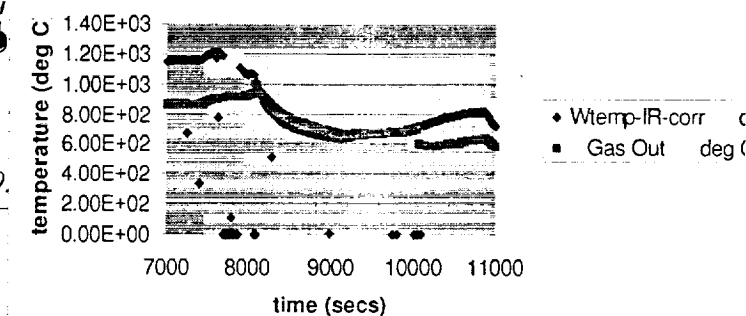


FIGURE 9. Time versus temperature profile for gas test.

CONCLUSIONS

Full power nuclear tests of space fission systems are expensive, time consuming, and of limited use, even in the best of

programmatic environments. Non-nuclear tests are affordable and timely, and the cause of component and system failures can be quickly and accurately identified. If the system is designed to operate within established radiation damage and fuel burnup limits while simultaneously being designed to allow close simulation of heat from fission using resistance heaters, high confidence in fission system performance and lifetime can be attained through a series of non-nuclear tests.

The MUTT was successful at demonstrating the use of resistance heaters to realistically simulate heat from fission. Specifically, the MUTT showed a module temperature greater than 1477 deg C, an energy transfer capability of a greater than 1 kW from a heat pipe, heat pipe isothermal operation greater than 1177 deg C, different heat pipe start-up transients, and the ability of gas to extract heat from the module. The MUTT demonstrated the ability to use several different instrumentation techniques for measuring temperature and pressure in a simulated fission (thermal hydraulic) environment. Lessons learned will be used on the full 30 kw core test planned at MSFC, which is expected to be completed early 2001.

ACKNOWLEDGMENTS

RECOMMENDATIONS

This test series demonstrated that some aspects of fission system operation can be simulated using non-nuclear test facilities. Any future fission program, whose goal is a flight system, should investigate the use of non-nuclear testing where appropriate to significantly decrease programmatic cost. Data gained from such tests may be more thorough (i.e. failure testing and margin testing) since a great deal of the safety issues associated specifically with nuclear testing, such as hot cells, will not have to be addressed.

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